

Mapping the Galactic Halo. V. Sgr dSph Tidal Debris 60° from the Main Body

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ABSTRACT

As part of the Spaghetti Project Survey (SPS) we have detected a concentration of giant stars well above expectations for a smooth halo model. The position ($l \sim 350, b \sim 50$) and distance (~ 50 kpc) of this concentration match those of the Northern over-density detected by SDSS (Yanny et al. 2000; Ivezić et al. 2000). We find additional evidence for structure at ~ 80 kpc in the same direction. We present radial velocities for many of these stars, including the first published results from the 6.5m Magellan telescope. The radial velocities for stars in these structures are in excellent agreement with models of the dynamical evolution of the Sgr dwarf tidal debris, whose center is 60° away. The metallicity of stars in these streams is lower than that of the main body of the Sgr dwarf, which may indicate a radial metallicity gradient prior to disruption.

Subject headings: Galaxy:evolution — Galaxy:formation — Galaxy:halo — Galaxy:stellar content

1. Introduction

Decisive evidence is mounting in support of a Galactic halo predominately formed through mergers and accretion. High-redshift observations, and modern simulations of structure evolution within the framework of cold dark matter (Pearce et al. 1999; Steinmetz & Navarro 1999), suggest that large galaxies formed hierarchically through the progressive merger of smaller pre-galactic structures. Observational evidence of this process can be identified in fossil remains of past accretions or mergers in the Milky Way.

The remains of an accreted galaxy can be identified in the Galactic halo as coherent substructure in space (Johnston et al. 1996), velocity, or both (Helmi & White 1999; Harding et al. 2001). There are several examples of such coherent groups (Majewski, Munn, & Hawley 1994; Côté et al. 1993; Arnold & Gilmore 1992; Helmi et al. 1999). One of the most dramatic is the Sgr dwarf (Ibata et al. 1994) and its extension to at least 17 kpc to the SE (Mateo, Olszewski, & Morrison 1998), which demonstrates that galaxy accretion is a process that continues even today.

More recently Yanny et al. (2000) and Ivezić et al. (2000) found an over-density of blue horizontal branch (BHB) stars and RR Lyrae type stars, respectively, in Sloan Digital Sky Survey

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(SDSS) commissioning data. The over-density covers 35° on the sky and is located near $\alpha = 14.7$ h, $\delta = 0^\circ$ ($l = 351^\circ$, $b = 52$), 50 kpc from the Sun, and is 60° from the center of the Sgr dwarf. This structure has also been detected with carbon stars (Ibata et al. 2001), and CMD analysis (Martinez-Delgado et al. 2001). Very recently, this feature was also found by Vivas et al. (2001) as part of the QUEST RR Lyae type variable star survey. They also found an over-density of RR Lyrae stars at closer distances, partially associated with the globular cluster Pal 5, and partially without identification.

Comparison to models of the disruption of the Sagittarius galaxy (Johnston et al. 1999; Helmi & White 2001; Ibata et al. 2001) strongly suggests that this structure is tidally stripped material from the Sgr dwarf (Ivezic et al. 2000). However, none of the techniques to date have been able to confirm this with both distance and velocity data. As part of the Spaghetti Project Survey (SPS) (Morrison et al. 2000), we have serendipitously identified giants associated with the SDSS over-density, and measured their radial velocities and distances. The excellent agreement with model predictions leads us to conclude that this structure is, indeed, tidal debris from the Sgr dwarf. Furthermore, we have identified additional structures at different distances which may be multiple wraps of the Sgr dwarf tidal stream.

2. The Spaghetti Survey

The SPS is a photometric and spectroscopic survey designed to identify structure in the Galactic halo (Morrison et al. 2000). For this study we use the modified Washington photometric system (Canterna 1976; Geisler 1984) to identify candidate red giants. The $M - 51$ color index is sensitive to surface gravity, while $C - M$ gives a photometric abundance. Candidate halo stars MUST be observed spectroscopically to confirm the photometric classification and metallicity, and to obtain a radial velocity.

By chance, a number of survey fields with existing photometry and spectroscopy lie near the direction of the SDSS over-density. We will focus on 16 of these fields which lie in the region defined by $300 < l < 360$, $0 < b < 30$, and $30 < b < 70$, and were imaged in April 1999 (Dohm-Palmer et al. 2000). A complete list of these fields, and the stellar photometry, is available through the NASA ADC database (<http://adc.gsfc.nasa.gov>).

We applied our giant selection criteria (Morrison et al. 2001) to the photometry from this subset of fields. In order to include some fainter, potentially more distant giants in our first spectroscopic observations with Magellan, we relaxed the $M - 51$ error selection limit, which is the most crucial (Morrison et al. 2001), from 0.02 to 0.032 magnitudes, matching the largest error among all previously confirmed giants in these fields. There are 32 giant candidates, of which 21 have been confirmed spectroscopically using the criteria of Morrison et al. (2001). These are listed in Table 1.

The photometric metallicity (Morrison et al. 2000), coupled with globular cluster giant

branches Da Costa & Armandroff (1990), transformed to $M - T2$ (Morrison et al. 2001), allows us to determine the absolute magnitude of each star. The metallicity determined in this way is subject to errors of order 0.3 dex, which leads to distance errors of about 25%.

The spectra for the six most distant giants are shown in Fig. 1, along with two standards for comparison. Star l355.89b+51.10 was observed on 20-22 February 2001 with the newly commissioned 6.5m Magellan I telescope at Las Campanas, with the LCO B&C spectrograph. Details of the spectral reduction process can be found in Mateo et al. (2001). Both velocities (Mateo et al. 2001) and preliminary metallicities (Morrison et al. 2001) were determined from the spectra. Velocities are accurate to 20 km/s. In most cases the agreement between the spectroscopic and the photometric metallicities is better than 0.2 dex. The photometric value is listed in Table 1, with the exception of l356.15b+50.95, whose preliminary spectroscopic metallicity differed significantly from the photometric value.

3. Model Comparison

Fig. 2 is a histogram of the heliocentric distance for all giant candidates. The filled histogram is the subset of candidates that have been confirmed to be giants spectroscopically. The curve is the predicted number of giants based on a model from Morrison (1993) for a smooth $R^{-3.5}$ halo. The model is normalized using the local halo giant density (Morrison 1993), and has an axial ratio variation prescribed by Preston, Sheckman, & Beers (1991). A model was made for each of the 16 selected fields, including a bright cutoff limit which varied from field to field, and a constant faint cutoff at $V = 20$.

There is a concentration of candidates between 40 and 60 kpc, matching the distance of the SDSS over-density. Of these, four stars have radial velocities. Based on our success rate for stars at this magnitude, we expect approximately half the remaining candidates at this distance will be confirmed to be giants, and the other half will be revealed to be subdwarfs (Morrison et al. 2001). Taking this into account, there remain 3-4 stars in each of the three bins near 50 kpc, where we only expect 1-2 stars.

Even more striking is the correlation of radial velocities for stars in this structure. The velocities of the four stars with spectra are remarkably similar ($\sigma = 31.5$ km/s) compared to the velocity dispersion of all confirmed giants ($\sigma_{\text{obs}} = 150.2$ km/s). This association is certainly indicative of a coherent structure.

The models developed by Helmi & White (2001) predict that the Sgr dwarf corresponds to only the central region of a much larger, at least a few times $10^8 M_{\odot}$, progenitor. These models predict that a large amount of mass would be expected in streams, which can either be stellar or dark-matter dominated. In Fig. 3 we plot the heliocentric distance and radial velocity for the particles in their stellar model which fall within our selected region of the sky. We have also plotted the locations of all candidate giants with measured radial velocities. The four stars near 50 kpc are

shown with filled circles, and match very well both the distance and radial velocity found in the models.

In addition to the concentration of giant candidates near 50 kpc, there is one near 20 kpc and one near 80 kpc (Fig. 2). The radial velocities of most of the stars near 20 kpc (Fig. 3) match the predictions for the Sgr dwarf streams, however, the range of predicted velocities at this distance is so large that this cannot be considered strong support for these being associated with the Sgr dwarf tidal debris. It is interesting to note that if most of these 20 kpc stars are indeed Sgr debris, then the smooth halo density at this distance must be much lower than simple models predict. This would suggest a large fraction of the halo may be composed of stream-like structures, even as close as $R \sim 20$ kpc.

In contrast to the ~ 20 kpc concentration, the two stars at 80 kpc show a spatial density and a velocity correlation above that expected from a smooth halo. Their position and velocity match model predictions for an earlier “wrap” of the Sgr dwarf tidal stream.

We compared the distance and velocity distribution of the 21 candidates with that of a smooth halo model. The smooth halo has an $R^{-3.5}$ density profile, and a radially anisotropic velocity ellipsoid with $\sigma = 135$ km/s. We performed 10,000 Monte Carlo simulations of 21 stars drawn from the smooth halo, including observational errors. The fraction of simulations which gave the observed distribution of 4 stars near 50 kpc with velocity dispersion of 32 km/s, and 2 stars near 80 kpc with velocity dispersion 21 km/s, was 11 in 10,000. We also performed this same exercise by drawing the samples from the model of the Sgr dwarf (Helmi & White 2001). Nearly 70% of these 10,000 samples result in the observed distribution. Thus, the likelihood that these stars belong to a smooth halo is negligible.

The present data cannot be used to make a full comparison to the spatial density of the model stream. In particular, the spatial sampling of our fields, at this point, is too sparse to determine the width or direction of the stream, and numerous selection effects must be addressed. We can only note that the confirmed members at 50 kpc are spread over 16° in longitude. If the two stars at 80 kpc are included the spread is over 50° in longitude. Furthermore, a detailed density comparison, for example, to determine if the 20 kpc stars are part of a stream or part of a smooth halo, must await a larger area to be studied, preferentially located far away from the expected sky position of the Sgr streams (Helmi et al. 2001).

Finally, we note that the mean metallicity of the six stars we claim to be part of the Sgr stream ($[\text{Fe}/\text{H}] \sim -1.5$) is about 0.5 dex lower than the mean for field stars in the main body of the Sgr galaxy (Layden & Sarajedini 1997; Mateo, Olszewski, & Morrison 1998). Many dSph galaxies show radial gradients in their horizontal branch (HB) morphologies, such that the outer HB stars are bluer (Caldwell et al. 1998; Hurley-Keller et al. 1999; Da Costa et al. 2000; Harbeck et al. 2001). Since the outermost stars are preferentially stripped during tidal disruption (Piatek & Pryor 1995; Oh, Lin, & Aarseth 1995), the streams could exhibit a different HB population than the more tightly-bound core. This could explain why the SDSS over-density consists of large numbers

of blue HB stars, while such stars are mostly absent in the core of Sgr. This is also consistent with the lower metallicity of the stream stars if the HB morphology gradient reflects an underlying metallicity variation in Sgr.

The destruction of dwarf galaxies is probably a crucial element in building up the stellar halo of our Galaxy. With further observations, the age information that we can recover from the different wrappings, combined with the metal abundances of the stream stars, will give a detailed observational picture of the progressive destruction of this galaxy. Deriving the chemical enrichment and star formation as a function of time and position in the Galaxy will, for example, help us understand the effect of tides on the internal evolution of such apparently fragile systems. Mapping the streams of Sgr will also provide some strong constraints on the large scale evolution of the shape and structure of the Galactic potential on Gyr time-scales, and on the amount of dark matter substructure.

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Fig. 1.— The spectra of the 6 stars beyond 40 kpc, and two standard stars. G194-37 is a known subdwarf with $[\text{Fe}/\text{H}]=-2.0$, and N4590-71 is a globular cluster giant with $[\text{Fe}/\text{H}]=-2.1$. The tick marks indicate the zero flux level for each successive star. The dotted lines mark three spectral indicators used to distinguish dwarfs from giants: Ca II K (3934Å), Ca I (4227Å), and Mg b (5167Å). Note that the subdwarf has a much stronger CaI line than any of the distant giants.

Table 1. Confirmed and Potential Giants Associated with Sgr Tidal Debris

Star	V_0	$(M - T_2)_0$	[Fe/H] ^a	M_V	Dist. (kpc)	Helio. Vel. (km/s)
l003.06b+61.30	19.21	1.174	-1.8	0.830	47.5	12
l011.85b+51.95	17.57	1.192	-1.3	0.720	23.4	-143
l017.04b+46.40	16.81	1.130	-1.7	1.097	13.9	56
l017.35b+46.50	16.53	1.237	-1.5	0.200	18.3	112
l301.78b+45.46	16.68	1.130	-1.8	1.059	13.3	
l302.36b+49.04	17.38	1.255	-3.6	-0.007	30.0	
l302.43b+48.83	19.86	1.136	-1.5	1.141	55.5	
l304.49b+60.51	18.90	1.363	-1.8	-0.922	80.0	63
l304.69b+60.52	16.86	1.197	-1.8	0.276	20.7	278
l305.22b+61.24	17.24	1.187	-1.8	0.307	24.4	56
l305.32b+60.58	16.91	1.177	-1.7	0.484	19.2	-62
l305.44b+61.34	16.38	1.178	-1.1	0.938	12.3	
l305.50b+60.65	17.52	1.370	-1.0	-0.204	35.1	207
l322.12b+39.91	16.18	1.180	-1.4	0.772	12.1	329
l322.18b+40.02	19.51	1.120	-2.2	0.889	53.1	
l326.26b+49.00	17.79	1.236	-1.6	0.176	33.4	-68
l332.71b+46.84	17.64	1.144	-1.5	1.050	20.8	142
l333.34b+46.51	19.10	1.111	-1.6	1.331	35.7	
l333.50b+46.75	18.27	1.138	-1.3	1.179	26.1	76
l338.85b+68.27	16.66	1.218	-2.4	-0.037	21.9	-28
l340.15b+68.30	19.49	1.169	-1.5	0.823	54.1	
l347.28b+53.30	19.06	1.163	-1.7	0.882	43.2	84
l347.42b+53.31	16.50	1.208	-1.5	0.437	16.3	169
l347.68b+53.06	17.02	1.121	-1.8	1.107	15.2	-119
l354.95b+66.01	19.86	1.149	-1.6	0.992	59.3	
l355.89b+51.10	19.86	1.232	-1.4	0.346	80.0	33
l355.99b+51.16	16.90	1.187	-1.5	0.626	18.0	-113
l356.15b+50.95	18.26	1.304	-1.5	-0.290	51.1	47
l356.54b+51.18	19.10	1.221	-1.0	0.724	47.3	
l356.70b+51.23	17.16	1.446	-1.6	-1.072	44.2	25
l356.81b+51.06	19.28	1.146	-1.4	1.088	43.5	
l356.88b+51.09	19.14	1.138	-1.3	1.200	38.8	

^aAll metallicity determinations are photometric, except that for star l356.15b+50.95, which is a preliminary spectroscopic measurement.

Fig. 2.— A histogram of giant candidates in heliocentric distance. The giants stars come from 16 selected fields with Galactic coordinates $300 < l < 360, 0 < b < 30, \text{ and } 30 < b < 70$. The shaded histogram shows all spectroscopically confirmed giants. To match the largest error of a confirmed giant, we have included all candidates with a $M - 51$ error < 0.032 . Given this error limit, we expect approximately half the unconfirmed stars near 50 kpc are actually metal-poor subdwarfs. The solid line is a model prediction from a smooth $R^{-3.5}$ density profile, based on the selected fields observed. Note the over-densities at 50 and 80 kpc, and possibly near 20 kpc.

Fig. 3.— Distance versus radial velocity for the Sgr dwarf stellar models of Helmi & White (2001). The model points come from the range $300 < l < 360, 0 < b < 30$. In the top panels they have been divided into three latitude bins, while all latitudes are included in the bottom panels. Also plotted in the top panels are the giants with measured radial velocity. The diamonds mark the two most distant giants at 80 kpc, the filled circles mark the 4 giants near 50 kpc, the triangles mark stars matching the model near 20 kpc, and the open circles mark stars that don't match the model within their error box. The bottom left plot shows the same data as the top panel, except not split into latitude bins. For comparison, we plot in the bottom right one of the 10,000 Monte Carlo simulations of 21 stars drawn from a smooth halo population.





